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86228 Spartan Service Module Finite
Element Modeling Technique and
Analysis

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Spartan Service Module Finite Element Modeling Technique and Analysis

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Information Branch

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INTRODUCTION

Purpose

The Spartan Program saw its first launch on the Space Shuttle and completed a successful mission in June of 1985. This culminated years of work designing, building, analyzing, and qualifying the structure for flight certification. Spartan 101, the first of a series of payloads to follow, was built up from a primary structure of welded tubular frames. The next generation of Spartans, the 200 series, incorporated a reusable primary structure acting as a service module that is built up of machined plates bolted together along with unique upper structures.

The purpose of this paper is to describe the Spartan carrier system and the finite element modeling technique and analysis that was used to qualify the service module for flight certification.

Scope

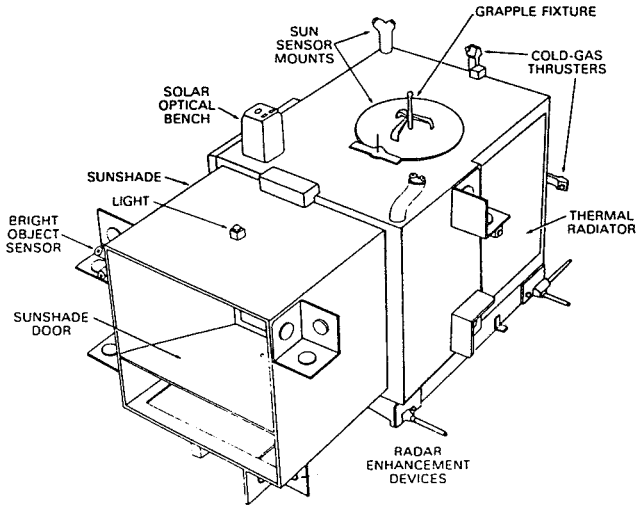
The scope of this paper is general in nature with all detailed calculations omitted. Specific calculations and model input data are documented in the Spartan Service Module Analysis notebook that can be made available for inspection by this author.

SPARTAN OVERVIEW

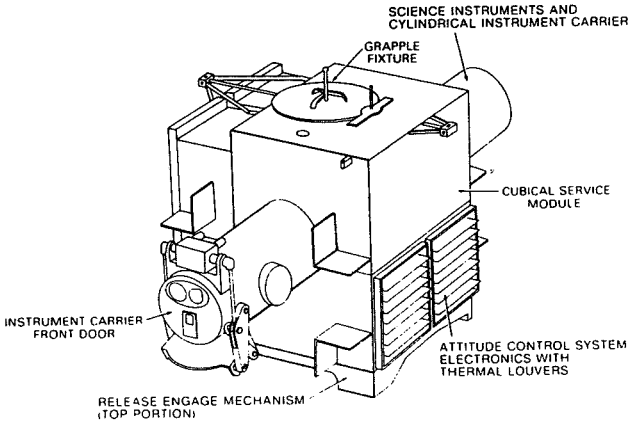
For over 20 years NASA has been conducting relatively inexpensive scientific research using sounding rockets to carry instruments into the upper atmosphere. Sounding rockets continue to be an essential tool for obtaining quick and reliable information on the nature of the upper atmosphere and astronomical phenomena in general. The opportunity now exists to place a sounding rocket type experiment into Earth orbit by the Space Shuttle. Spartan substitutes as the sounding rocket carrier and accommodates either existing or new scientific experiments. The program provides valuable increases in observation times and pointing capabilities.

The Space Shuttle will transport Spartan to space where the remote manipulator system will grapple Spartan, deploy it and allow it to act as a free flying autonomous subsatellite. All observations and data collection are stored on a tape recorder and attitude control system pointing maneuvers are preprogrammed. After an orbiting duration of up to 40 hours, Spartan will be retrieved by the orbiter and returned to earth. The carrier system is reusable, with an approximate turnaround time of 6 to 9 months, and each flight specifically adapted to the experimenter's requirements (1).

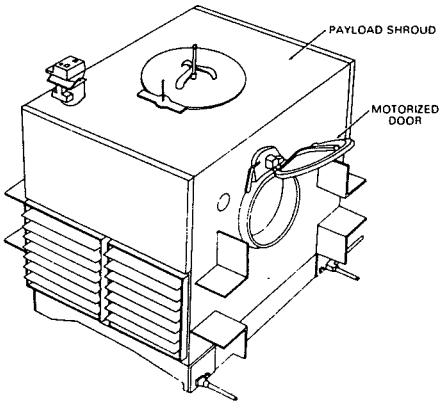
In addition to the completed Spartan 101 mission, there are presently three other missions scheduled to fly in the near future. The Spartan 101 carrier, supporting high-energy astrophysics, provided a structure with an optical bench to accommodate a variety of rectangular array detectors designed to point at stellar objects. Spartan 201, supporting solar physics, will accommodate a 17 inch diameter telescope and will use a solar fine-pointing capability to allow it to view selected points on the surface of the sun. It is scheduled for launch in October 1986. The Spartan 202 carrier, supporting ultraviolet astronomy, will use a stellar fine-pointing system similar to the one developed for Spartan 101 and is scheduled for launch in late 1986. Finally, the Spartan 203 carrier will be dedicated to observing the Halleys comet rendezvous, with its launch scheduled for January 1986 (2). Figure 1 illustrates the configurations of the first four Spartan missions. More information on the Spartan program and newly selected payloads may be found in Reference 3.



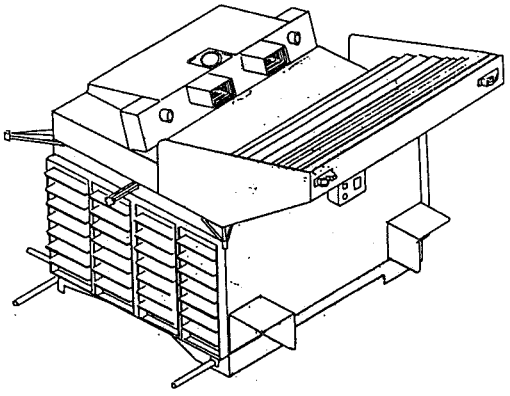
(a) SPARTAN 101


SCIENCE INSTRUMENTS AND CYLINDRICAL INSTRUMENT CARRIER
GRAPPLE FIXTURE
CUBICAL SERVICE MODULE
INSTRUMENT CARRIER FRONT DOOR
ATTITUDE CONTROL SYSTEM ELECTRONICS WITH THERMAL LOUVERS
RELEASE ENGAGE MECHANISM (TOP PORTION)

(b) SPARTAN 201



(c) SPARTAN 202



(d) SPARTAN 203

Figure 1. Spartan Payloads.

SPARTAN CARRIER SYSTEM

Spartan Flight Support Structure (SFSS)

The Spartan deployable payload is supported in the orbiter bay by the SFSS which consists of the main across-the-bay structure known as the Mission Peculiar Equipment Support Structure and the Release Engage Mechanism (see Figure 2).

Mission Peculiar Equipment Support Structure (MPESS). The MPESS is a bridge structure that is attached to the cargo bay through keel and trunnion fittings (see Figure 2). It was designed to carry a 2640 pound Spartan deployable (fly-away) and may be located at several positions along the cargo bay. The MPESS spans 16.2 feet across the bay, is 2.6 feet wide, and is 9.3 feet in height. Total weight of the MPESS, including the Mission Peculiar Equipment, is 1980 pounds.

Release Engage Mechanism (REM). The REM is the interface hardware between the Mission Peculiar Equipment on the MPESS and the Spartan deployable. It allows the Spartan to be attached to and detached from the SFSS. The bottom half of the REM remains attached to the MPESS whereas the top half, the REM adapter, is an integral part of the Spartan deployable. It measures 59 by 47 by 6.5 inches and weighs 331 pounds. See Figure 3.

Service Module and Instrument Carrier

The service module is the main component of the Spartan 200 series type payloads and is modular and universal in design. Originally developed for the Spartan 201 mission, it is now being used as the primary structure for all of the 200 series missions. Unique upper structures, or instrument carriers, with the user's experiments and associated systems are attached to the service module and complete the Spartan deployable portion of the carrier system.

The service module, housing the Spartan's support systems (power, data-handling, and attitude control), is built up from 2219-T851 aluminum alloy machined frames that are bolted together. Its dimensions are 51 by 43 by 34 inches. Including support systems, it weighs approximately 1500

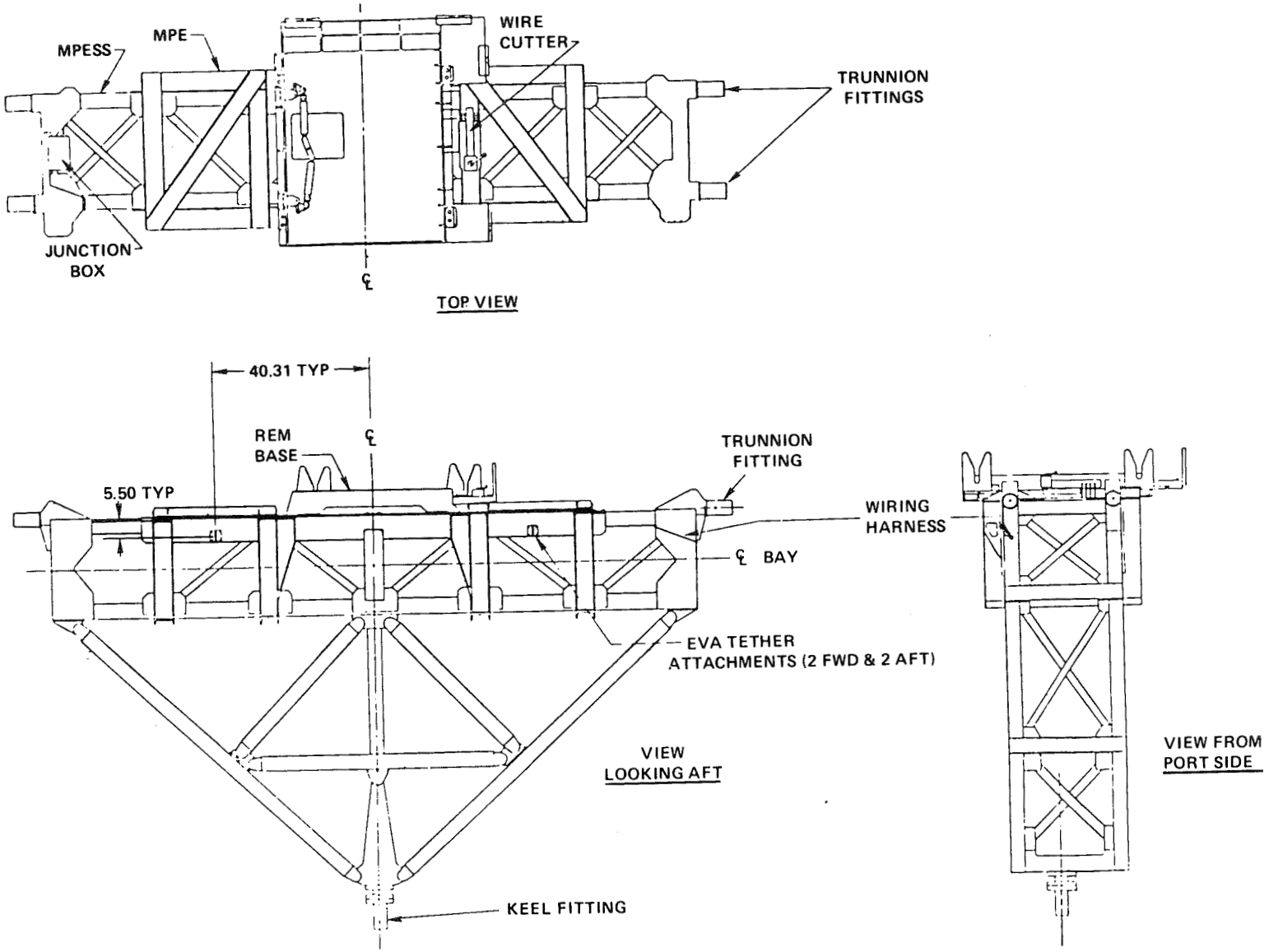


Figure 2. Spartan Flight Support Structure.

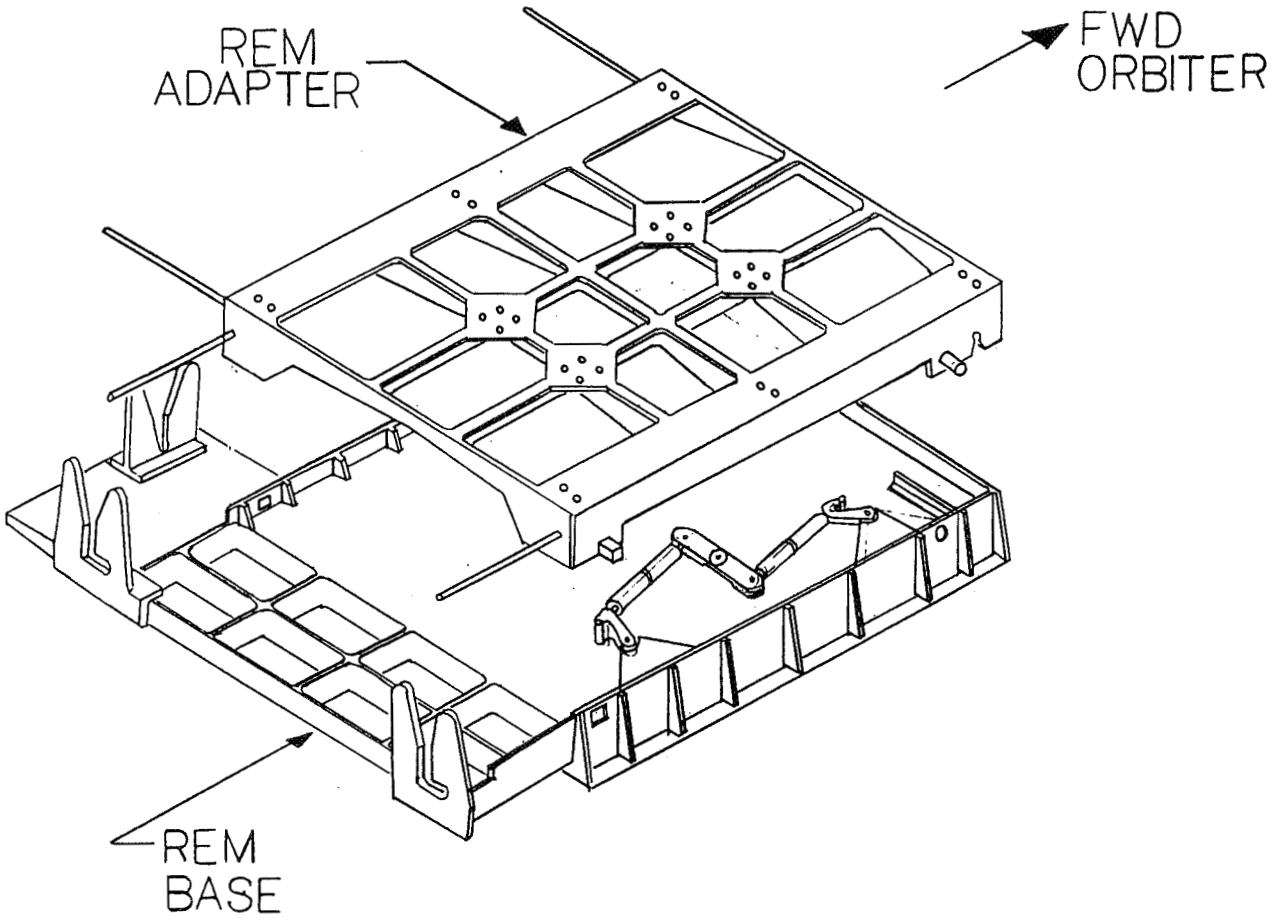


Figure 3. Spartan Release Engage Mechanism.

pounds. An illustration of the module is shown in Figure 4. Since the service module is reusable and is the primary structure for the 200 series payloads, it was important that it have high structural integrity and a long useful life. The remainder of this paper is dedicated to the analysis of the service module illustrating how the above goals were met.

SERVICE MODULE FINITE ELEMENT MODEL GENERATION

Modeling Technique

The general purpose NASTRAN finite element program has been used extensively throughout NASA and industry for formal structural analysis of complex structures. It is very versatile and generally accepted as a proven and verified method of analysis. It was chosen as the code to be used in performing the analytical work on the service module.

The COSMIC NASTRAN version used, however, does not support any pre- or post-processing capabilities. It requires the model of a structure to be input in fixed format, point by point, element by element. It does not have any interactive graphic capabilities or other advanced model generation techniques.

Most of the work performed by the Code 741 has been completed using this version of NASTRAN. Since the Spartan 200 series payloads, however, we have adopted a new technique of model generation using the Graphic Interactive Finite Element Time Sharing System (GIFTS) as a preprocessor. GIFTS, developed at the University of Arizona, is a finite element analysis package with its own static and dynamic computing capabilities. Used as a preprocessor to NASTRAN, its many advanced model generation capabilities are accessed and significantly decrease model development time.

Listed below are some of the more powerful modeling capabilities of GIFTS.

1. Simple mesh generation. Allows the user to fill an enclosed boundary with automatically numbered grid points and elements by specifying boundary lines.

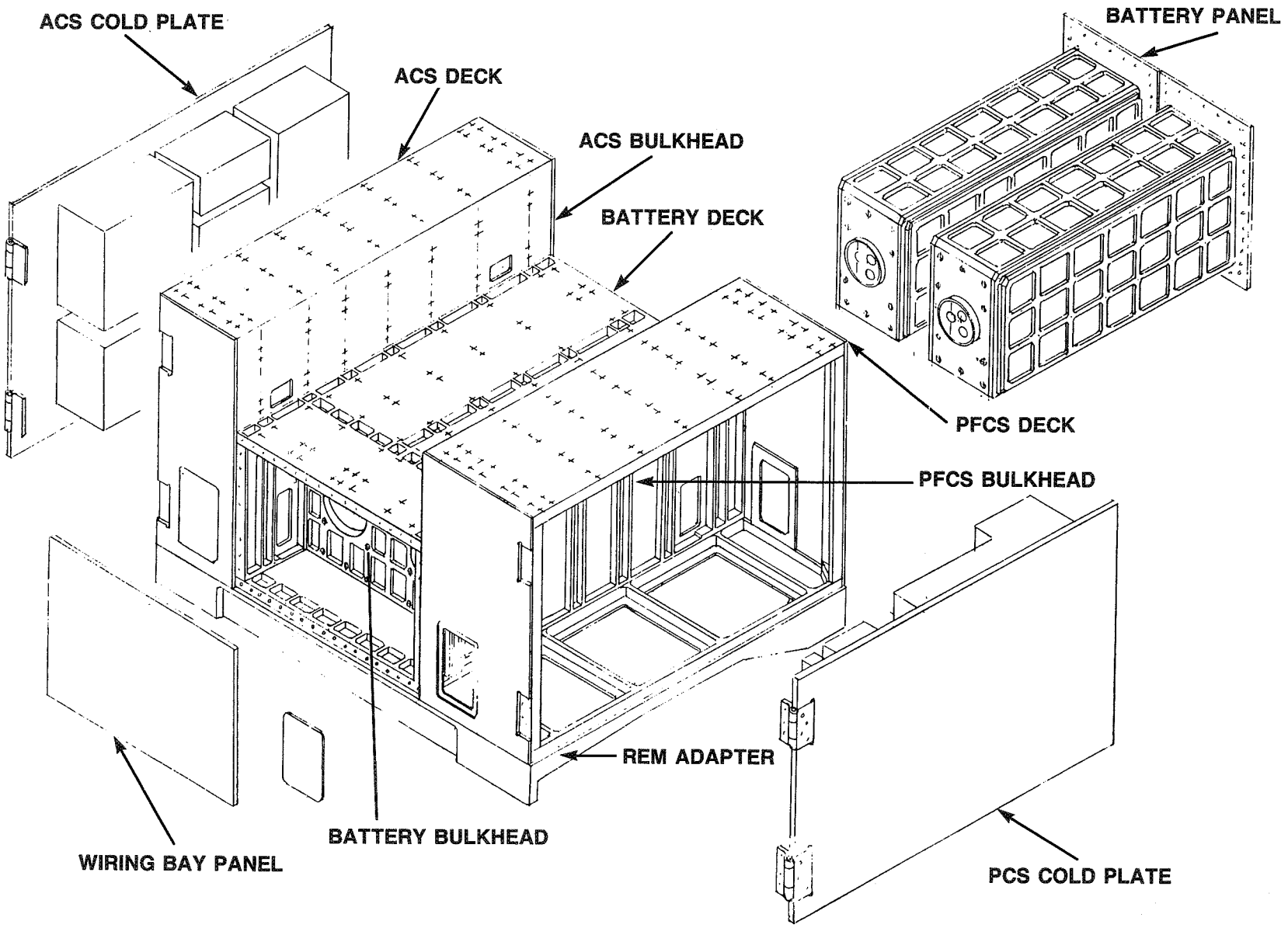


Figure 4. Spartan Service Module.

2. Extensive beam element library. Generation of standard or general cross section beam elements is simplified by accessing beam formulas stored in a library of subroutines.
3. Interactive graphics. Allows the user to view plots of the model at any point in the model generation. Views may be rotated, boxed and windowed interactively. In a postprocessing mode, deformed structure and stress contour plots are available.
4. Digitized input. Model generation may be simplified further by inputting data through a digitizing tablet. Points may be digitized directly off a scaled drawing. Also, GIFTS commands may be entered off the tablet through a user defined menu.

After model generation is complete, the data may be transformed into NASTRAN format through an interface program called GFTNAS. At this point, NASTRAN features may be implemented and the job is submitted for computation and results. This modeling technique has enabled greater designer/analyst interaction and the design process may be iterated until the optimal configuration is obtained. Figure 5 is a flowchart outlining the analysis process.

The final model of the service module contained 3373 beam, quadrilateral and triangular bending elements connected by 1587 grid points for a total of 9522 degrees of freedom. It was intentionally modeled in such detail to allow for easy application of nodal masses and applied loads. Various upper structure models may be added to the primary structure allowing the system to be analyzed as a complete unit. A GIFTS plot of the service module model and plots of the model in the Spartan 201 and 203 configurations are given in Figures 6 and 7.

Design Criteria

The Marshall Space Flight Center performed a study on the suggested load factors for qualifying the Spartan REM. They determined that for a 2,500 lb payload supported by any available support structure located anywhere in the orbiter bay, limit load factors of ± 8, ± 4.5, ± 8 g's in the X, Y, and Z directions respectively are required. Goddard adopted this criteria in the design of all Spartan payloads.

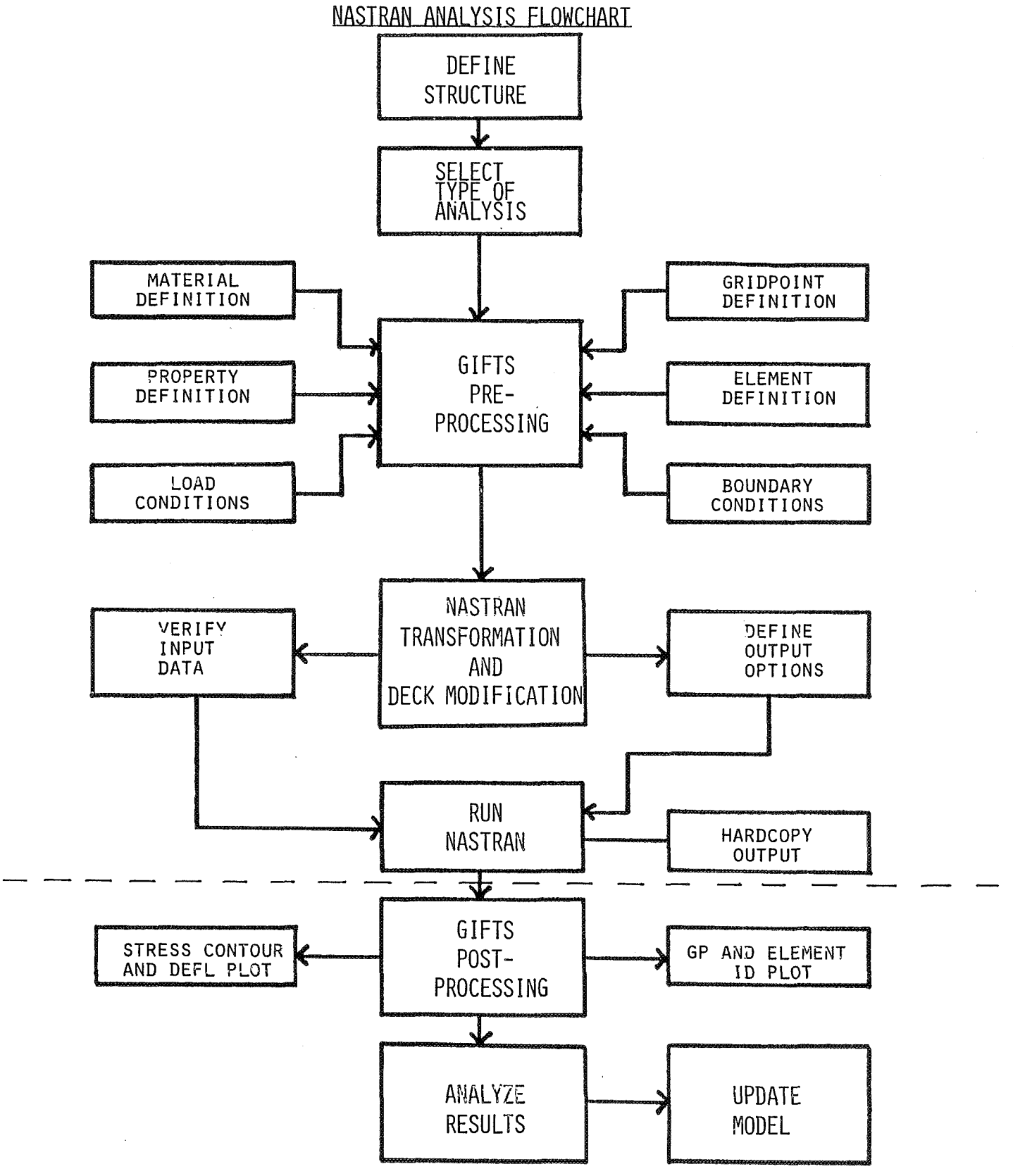


Figure 5. NASTRAN Analysis Flowchart.

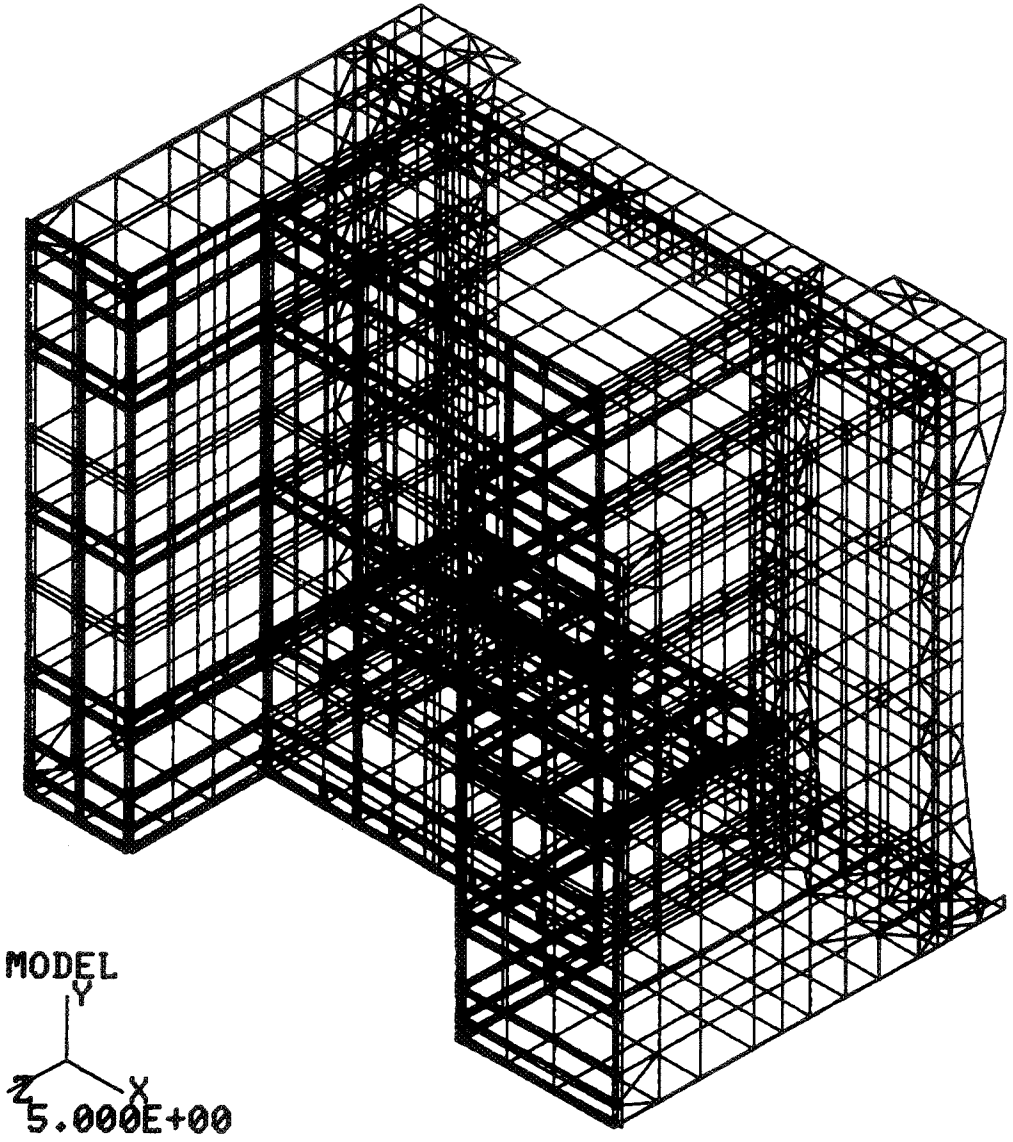
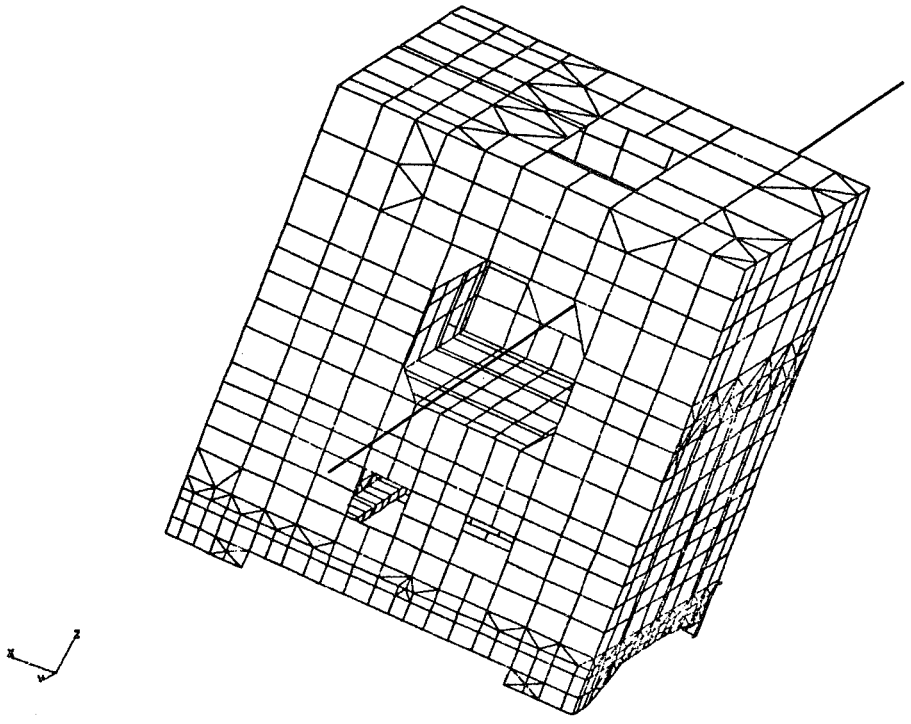
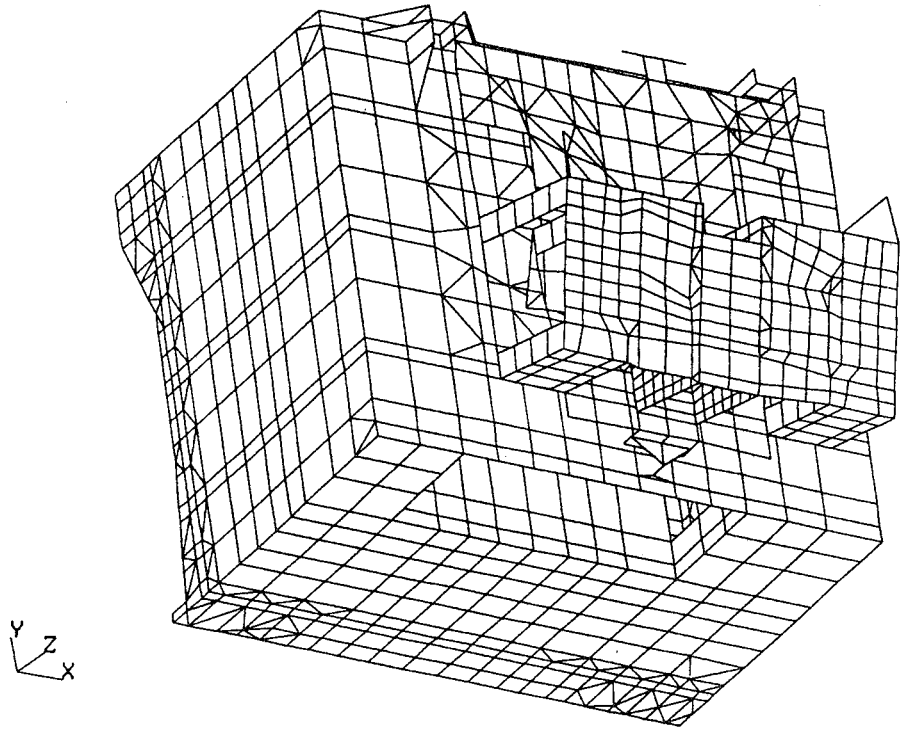


Figure 6. Service Module Finite Element Model.



(a) Spartan 201



(b) Spartan 203

Figure 7. Spartan 201 and 203 Finite Element Models.

The nature of the service module, i.e., reusable, universal, and long useful life, required conservative design factors. Thus, the analysis was completed with the above limit load factors and a yield factor of safety of 2.0 and an ultimate factor of safety of 3.0. These factors of safety are higher than the NASA standard requirements of 1.25 for yield and 1.4 ultimate. See Reference 4.

Load and Boundary Conditions

The model was subjected to a gravity load of two times the limit loads thereby incorporating the yield factor of safety into the results directly. With masses applied to the model to simulate the module's standard equipment and instrumentation, all possible load case combinations were considered.

The REM adapter, an integral part of the service module, interfaces the SFSS through four pins resulting in a semi-kinematic mount design. The two round pins take X, Y, Z and X, Z loads respectively, and the remaining two square slotted pins take Y, Z and Z loads respectively. These degrees of freedom were accurately reflected in the model allowing for realistic load paths to develop.

ANALYTICAL RESULTS

Stress Analysis

Service Module Components. The minimum margins of safety resulting from the service module static load cases are given in Table 1. The service module analyzed included a Spartan 201 upper structure enforcing a realistic load path through the structure as opposed to quasi-static acceleration loading on the module alone. As the table suggests, a worst case loading scenario occurs with the +X, −Y, +Z load case. This information was helpful in developing a test plan for structural verification. A graphic presentation of the stress state during this worst case loading scenario is illustrated in the GIFTS generated stress contour plot shown in Figure 8. All margins were positive indicating an acceptable service module design.

TABLE 1
SERVICE MODULE MINIMUM MARGINS OF SAFETY

SPARTAN 201 SERVICE MODULE MINIMUM MARGIN OF SAFETY SUMMARY

DESCRIPTION	LOAD CASE	$M.S._U$	$M.S._Y$
REM ADAPTER	+X,−Y,+Z	0.08	0.34
PFCS COLD PLATE	+X,−Y,+Z	2.96	3.40
ACS COLD PLATE	+X,+Y,+Z	3.40	3.89
PFCS BULKHEAD	−X,+Y,+Z	3.07	3.53
ACS ELECT. BULKHEAD	−X,+Y,+Z	1.05	1.28
BATTERY BAY DECK	−X,+Y,+Z	0.19	0.38
PFCS DECK	−X,+Y,+Z	0.77	0.97
ACS ELECT. DECK	+X,+Y,+Z	0.45	0.61
WIRING BAY COVER	+X,+Y,+Z	2.38	2.76
BATTERY BAY COVERS	+X,−Y,+Z	1.61	1.90
ACS/PFCS BAY END PLATE	−X,−Y,+Z	1.20	1.45
BATTERY BULKHEAD	+X,−Y,+Z	1.49	1.78

MATERIAL ALLOWABLES:

2219-T851 ALUMINUM ALLOY

F_{T_Y} = 46 KSI $\qquad$ FS_Y = 2.0

F_{C_Y} = 48 KSI $\qquad$ FS_U = 3.0

F_{T_U} = 62 KSI

F_{S_U} = 36 KSI

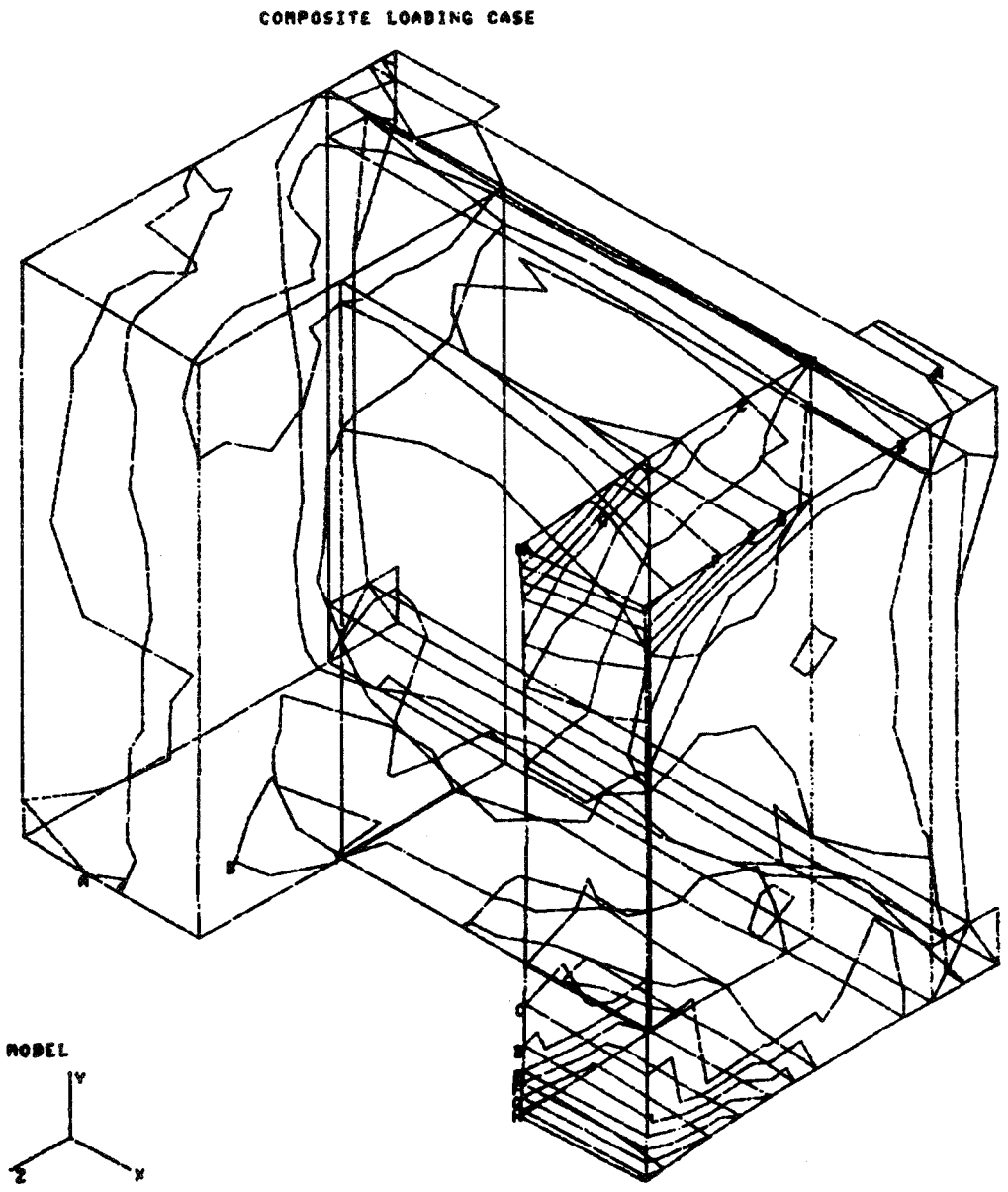


Figure 8. Service Module Stress Contour.

Fasteners. The entire service module is a bolted assembly. A NASTRAN grid point force balance analysis indicated that the number and size of bolts used in the assembly was adequate. Of particular interest was the REM adapter/data cold plate and cross bulkhead/ACS bulkhead interfaces. A detailed review of these areas resulted in a shear minimum margin of safety equal to 7.8 and a tensile minimum margin of 0.43.

Natural Frequency and Normal Mode Extraction

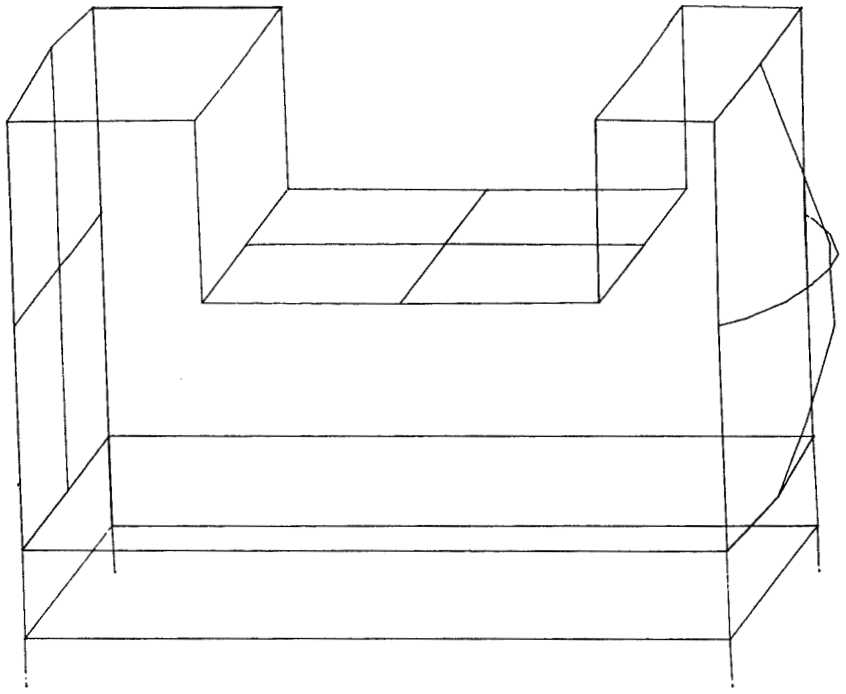
In addition to the static analysis reviewed above, a dynamic study of the service module was completed using the NASTRAN Fast Eigenvalue Extraction Routine (FEER) tridiagonal reduction method. Twenty eigenvalues were extracted with none of the off-diagonal terms failing the given criterion. The natural frequencies predicted ranged from a fundamental of 36 Hz to 303 Hz for the twentieth mode.

A service module modal survey resulted in a fundamental frequency of 50 Hz, indicating an apparent discrepancy between the actual results and the finite element approximation. The low modes of the structure occurred in the ACS and data cold plates. Actual experimentation on these cold plates produced additional stiffness due to the box-like structures that are bolted onto the plates, whereas, in the model, the extra weight of the equipment was simulated by distributed lumped masses with no inherent stiffness. This variation justifies the frequency discrepancy, especially since the mode shapes were nearly identical.

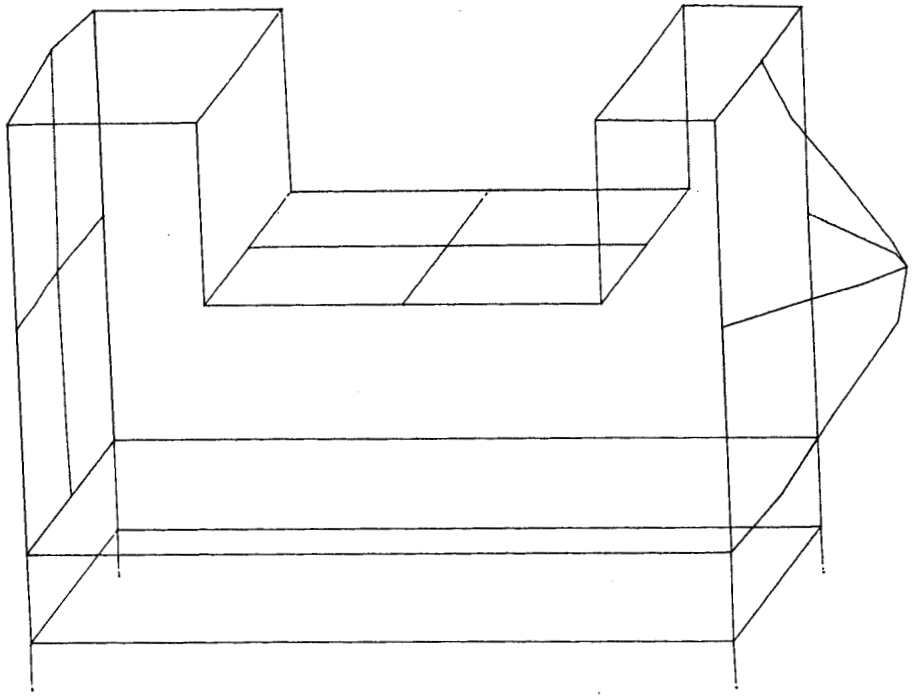
A comparison of the NASTRAN predicted modes and the first four modes from the modal survey are shown in Figures 9 through 12. They indicate that the model correlates closely to the empirical results and this, therefore, verifies the model's static and dynamic approximations.

TESTING AND VERIFICATION

A comprehensive test program has been developed to examine the physical characteristics and verify the structural integrity of the service module. As mentioned above, a modal survey was performed indicating the natural frequencies and mode shapes of the structure.

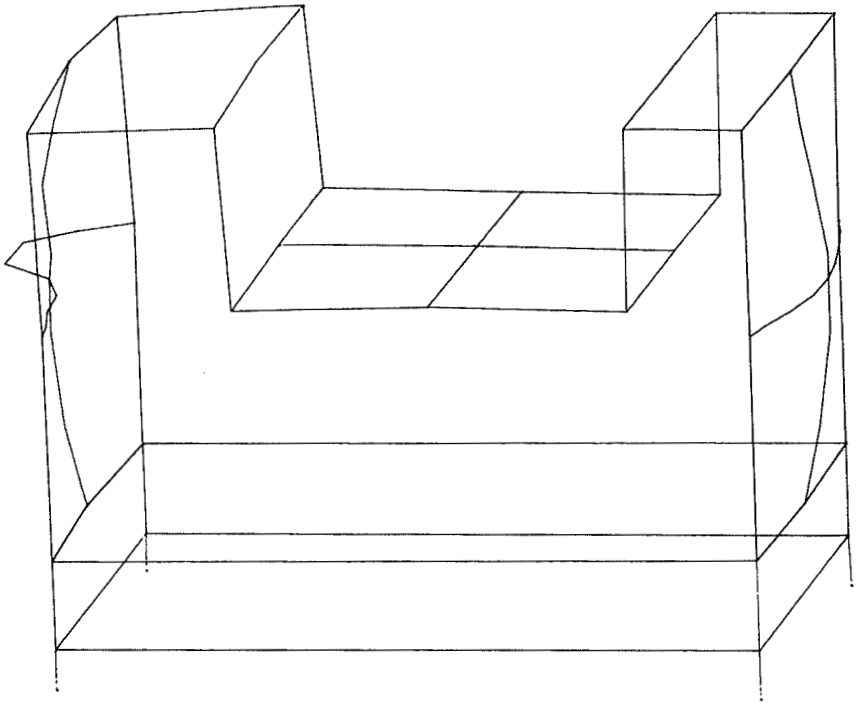


QTU FUNDAMENTAL ACS PANEL MODE
1:1090X- REAL.F= 50.013 HZ (-619.0. 3991.0. 688.0. 136.2)=VIEW

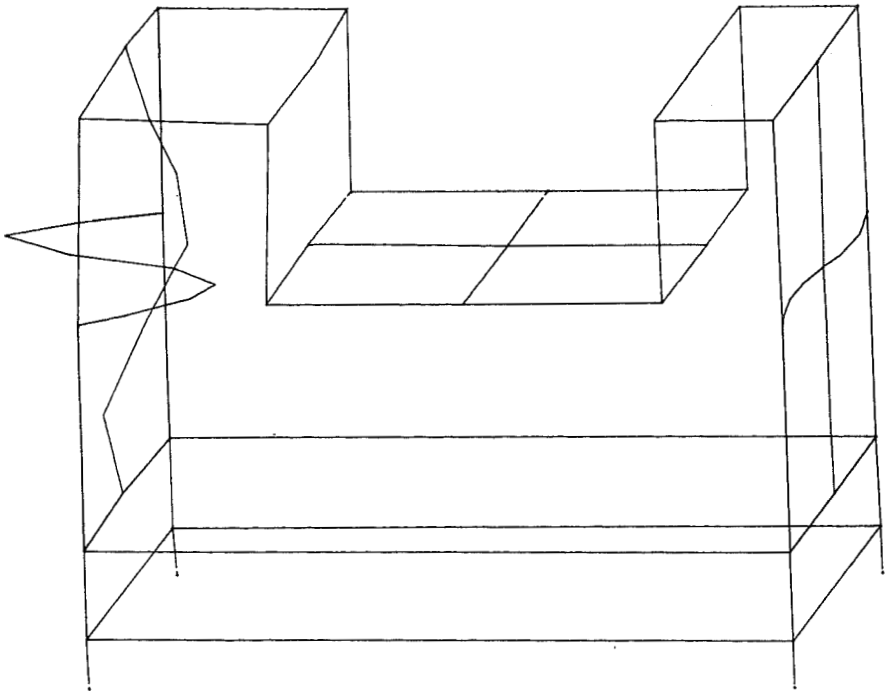


NASTRAN FUNDAMENTAL MODE OF ACS COLD PLATE
2: 0 REAL.F= 41.552 HZ (-622.0. 3990.0. 688.0. 136.4)=VIEW

Figure 9. Fundamental Mode of Service Module.

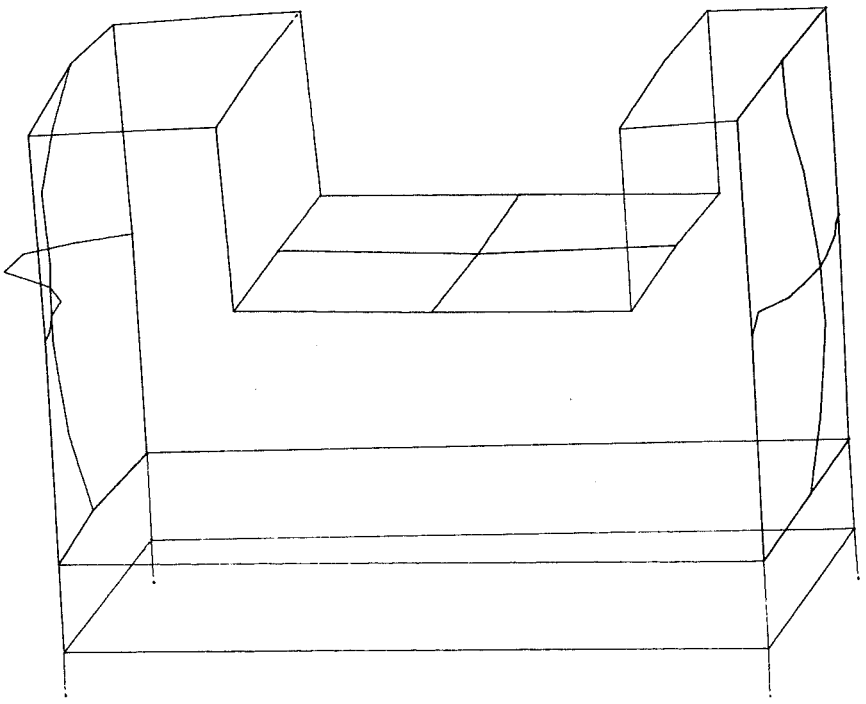


QTU 1ST ORDER DATA COLD PLATE MODE SHAPE
2:1090X- REAL.F= 68.741 HZ (-619.0. 3990.0. 688.0. 136.1)=VIEW



NASTRAN HIGH ORDER MODE FOR DATA COLD PLATE
6: 0 REAL.F= 67.683 HZ (-622.0. 3990.0. 688.0. 136.4)=VIEW

Figure 10. Second Mode of Service Module.



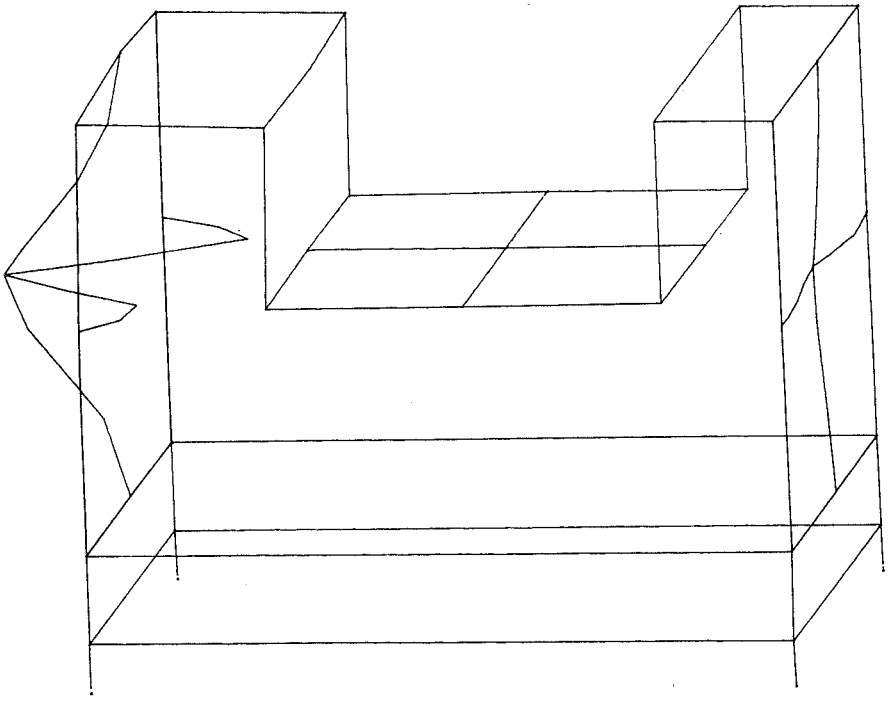
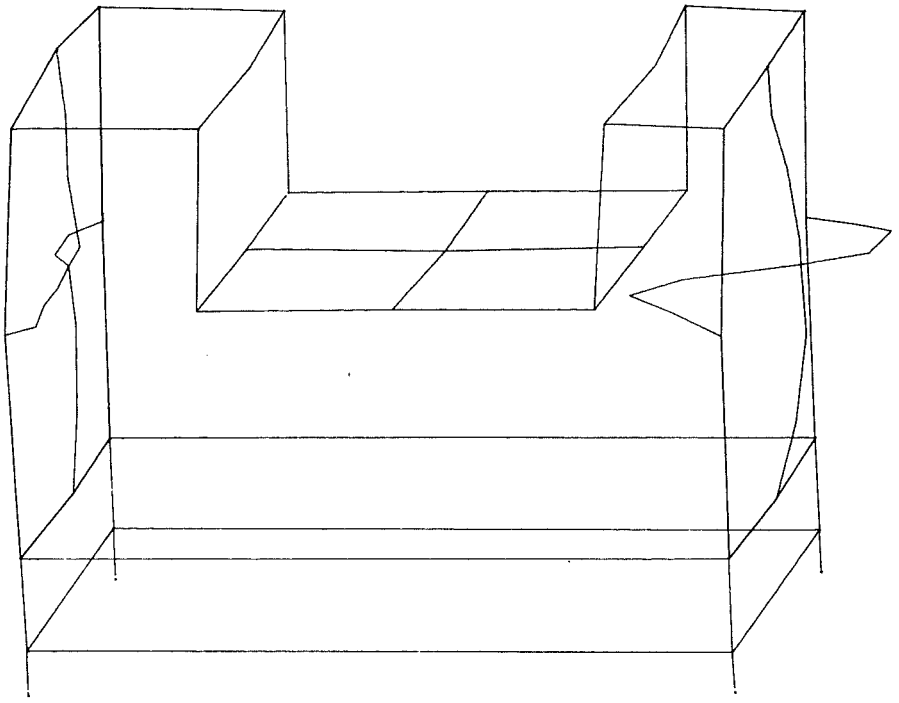
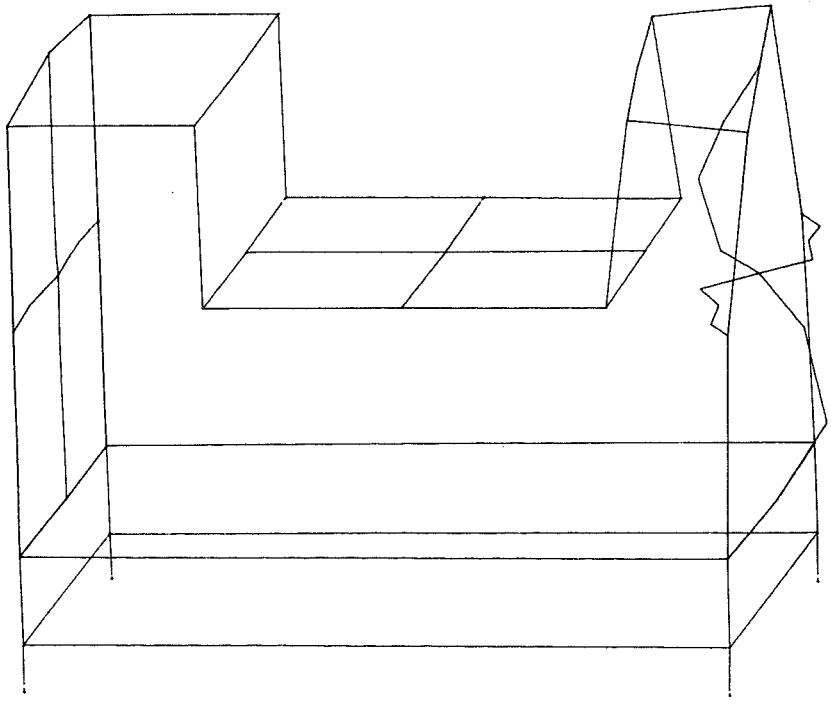


Figure 11. Third Mode of Service Module.



QTU 2ND ORDER ACS COLD PLATE SHAPE
4:1090X- REAL.F= 88.910 HZ (-619.0. 3990.0. 688.0. 136.1)=VIEW



NASTRAN ACS EAR TORSION
11: 0 REAL.F= 89.229 HZ (-622.0. 3990.0. 688.0. 136.4)=VIEW

Figure 12. Fourth Mode of Service Module.

For the next series of tests, the service module was mated with the Spartan 201 upper structure. This was done to qualify both the 201 configuration and the service module for other Spartans at the same time.

A three axis random vibration test was performed measuring the transmissibility of various subassembly attachment points with respect to a base excitation. The test criteria for all three axes was identical to that previously used to qualify Spartan 101, which is now flight certified and launch ready. See Reference 5 for detailed test procedures. An acoustic test qualified the structure for a vibracoustics environment that is 3db above the flight acceptance levels. These levels were again identical to those used to qualify Spartan 101. See Reference 6.

A Launch Phase Simulator (centrifuge type) test, not completed at this time, will consist of three load cases. The load vectors will proof test the structure to 1.25 times the design limit loads of 8, 4.5, and 8 g's for a 3000 lb Spartan. Results of the stress analysis indicated that of all load combinations, three worst case loading orientations were significant, and these are the load vectors that will be used for the test. Reference 7 lists actual load vectors and pin reactions expected during the test.

Completion of these tests will fulfill the structural requirements of the Space Transportation System for qualifying the Spartan service module for flight certification.

CONCLUSION

The Spartan carrier system is a useful tool for carrying sounding rocket type experiments into space. Incorporating a service module or primary structure into the Spartan deployable payload has allowed easy structural adaptations accommodating the various Spartan missions.

Use of the GIFTS finite element package as a preprocessor to NASTRAN has enabled greater designer/analyst real-time interaction and has led to optimal subcomponent designs. With its ad-

vanced graphic and automatic mesh generation capabilities, GIFTS has greatly reduced model generation time.

The service module stress analysis resulted in all components having positive margins of safety, thus meeting the design goal of developing a primary structure, universal in nature, easily adaptable to various upper structure configurations, and able to provide a long useful life. The dynamic analysis and modal survey of the structure resulted in a relatively high fundamental frequency of 50 Hz. Also, the model showed acceptable correlation factors with the empirical data, which verified the finite element analytical results.

Review of all analytical work and the results of the test program should qualify the Spartan service module for flight certification and aid in the certification of all Spartan payloads to follow.

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15. Supplementary Notes

16. Abstract

Sounding rockets have served as a relatively inexpensive and easy method of carrying experiments into the upper atmosphere. Limited observation time and pointing capabilities suggested the development of a new sounding rocket type carrier compatible with NASA's Space Transportation System. This concept evolved into the Spartan program, now credited with a successful Spartan 101 mission launched in June 1985. The next series of Spartans will use a service module primary structure. This newly designed reusable and universal component in the Spartan carrier system required thorough analysis and evaluation for flight certification. Using advanced finite element modeling techniques, the structure was analyzed and determined acceptable by meeting strict design goals and will be tested for verification of the analytical results.

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